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CRYOMAGNETICS AT NASA

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The basic interests of the NASA Lewis Reserach Center lie along the lines of propulsion. Research in the Magnetics and Cryophysics Branch is, therefore, primarily directed toward propulsion applications. However, since many other aspects of space deal with magnetics, other considerably broader fields of research are being investigated. Among the other specific areas of interest are magnetic shielding and cryogenic magnetic research directed toward transient, a-c, and steady-state applications. Each of the areas mentioned will be briefly discussed with the purpose of acquainting the reader with some of the specific problems and possible solutions.

Thermonuclear rocket propulsion appears to be one of the most promising of the systems proposed for long-distance space missions (ref. 1). The system depends, of course, on the attainment of a controllable nuclear fusion reaction, which has not as yet been accomplished. One of the reactions most desirable from a weight standpoint is the deuterium, helium 3 reaction:

$$D + He^3 \rightarrow He^4 + H + 15.1\times10^{10} \text{ Btu/lb}$$

$$\left.\begin{array}{l} D + D \rightarrow He^3 + \text{neutron} + 3.4\times10^{10} \text{ Btu/lb} \\ D + D \rightarrow \text{Tritium} + H + 4.1\times10^{10} \text{ Btu/lb} \end{array}\right\} \text{(Negligible reactions in this case)}$$

A powerplant configuration like that in figure 1 results. If the reactor temperature is kept high ~~(10^8 to~~ (10^9 °K) the reaction will take place as shown. The deuterium will combine with itself only very slightly. With limited production of neutrons ~~Since no neutrons are produced~~, extra shielding to protect the crew and apparatus is ~~unnecessary~~ minimized, and the charged particles yielded may be magnetically confined. The magnet serves to contain the plasma (a conglomeration of free electrons and ions) and is therefore called a "magnetic bottle".

Work is presently being done at Lewis that deals with an experimental magnetic bottle section, which represents one-third of the configuration shown in figure 2 (ref. 2). The design of this magnet, which will be capable of producing a field strength of 200,000 gauss, was aided by two physical properties:

(1) The field strength for a fixed current density increases with increasing magnet size.

(2) The resistivity of pure metals decreases drastically as cryogenic temperatures are reached (e.g., liquid hydrogen temperature).

The first property is shown by the following equation for field strength:

$$B = J \mu_o \lambda a_1 C \qquad (1)$$

The symbols and geometry are defined in figure 3. If a_1 is large, a correspondingly large field strength results. In the case of the NASA magnetic bottle section, minimum power dissipation was a requirement since a cryogenic fluid was to be used. The quantities α and β were specified by this consideration, and the selection of a_1 then determined the remaining coil parameters. The final structure of the magnet depended not only on the mathematical considerations discussed but also on the magnetic interaction forces, that is, the forces caused by large currents in proximity.

In order to utilize the second physical property, very high purity aluminum (99.9983 percent) was used as the conductor, and low temperature operation with liquid neon cooling was decided on. The selection of aluminum over other high purity metals available was governed by a property called magnetoresistance, the change in material resistivity with magnetic field, that is most easily detected at cryogenic temperatures for common conductors. Figure 4 shows how the resistivity and, as a result, the heat load, varies with the temperature and the magnetic field present. Since the magnet will be operating in the vicinity of 200,000 gauss, the resistivity will be that corresponding to the "saturated" portion of the curve (ref. 3).

At first glance, liquid neon appears to be a rather exotic choice for the refrigerant due to its lack of availability (18 ppm in the atmosphere). However, its advantages were numerous enough to outweigh its disadvantages. In the range of temperature operation considered, there are several possible cryogenic fluids:

	$^{\circ}F$	$^{\circ}K$
(1) Helium	-452.0	4.2
(2) Hydrogen	-422.9	20.4
(3) Deuterium	-417.1	23.6
(4) Tritium	-414.4	25.2
(5) Neon	-410.6	27.2

Since the fluid is to be used in direct contact with the magnet coils, which would be warm at times, hydrogen, deuterium, and tritium were ruled out because of the hazards involved in venting large quantities of hydrogen. Neon was selected over helium because the latent heat per unit volume of neon is about twice that of helium. This means that for equal volumes of helium and neon boiling off, neon will remove about twice as much heat as helium.

Figure 5 shows two of the twelve aluminum coils that will eventually be installed in the magnet housing. The cycle that results in cooling the coils by nucleate boiling of the liquid neon is shown in figure 6. Experiments dealing with plasma heating are being planned in conjunction with this high-field magnet in an effort to gain experience and research data necessary for further examination of the thermonuclear fusion process.

It is obvious that any propulsion system is useless for manned space travel if the passengers are not kept alive. Charged particles released from the sun, for example, could prove fatal to space travelers. As a result, much effort is being concentrated in the area of space shielding. Magnetic space shielding in particular may be attractive from the weight standpoint due to the fairly recent discovery of high-field superconducting materials (ref. 4). The feasibility of magnetic shielding depends, to a large extent, on the limitations of superconductors.

When a conductor reaches the superconducting state, its resistance goes to zero. Ideally, then, infinite current could pass through such a conductor with no power loss due to I^2R. Actually, however, a number of restrictions limit the usefulness of superconductors:

(1) They must be kept at low temperatures (0.35 to 19° K).

(2) A maximum amount of current (critical current) can be passed through the conductor without a return to its "normal" state.

(3) A maximum magnetic field (critical field) may be impressed on the conductor, which is dependent on the current as well as the external magnetic field and temperature.

Superconductivity, therefore, is essentially a thermodynamic state that is dependent on a number of important conditions. However, it is quite possible that extremely large superconducting magnets can be built which, if the configuration is correct, may adequately shield a space crew ~~completely~~ from charged particles. Some worthwhile configurations have been devised and others are being examined by a number of research scientists (ref. 4). While the configuration of such a shield is of prime importance, the so-called "critical field" and "critical current" aspects of the more basic problem are currently receiving the most attention.

Facilities are available at Lewis for the study of superconductors in high fields. Among the more important research tools is the 100,000 gauss water-cooled magnet, homopolar generator combination (ref. 5). The construction of this magnet is shown in figure 7, and the output characteristics of the homopolar generator and its layout are shown in figure 8. With this facility, many interesting discoveries have been made concerning hard superconductors. The points at which a superconducting material exhibits normal resistance, that is, its critical field and critical current points, are of considerable interest. Constant field plots as well as constant current plots were made on samples of niobium-tin wire both with and without copper cladding on the wire (see fig. 9). The tests were all conducted in liquid helium. Some data points show that the current at constant field was increased until normal resistance was attained. Others show that the field at constant current was brought up in a similar manner until the superconductor exhibited normal resistance. It is apparent that instability exists at the low regions of magnetic field. An analysis is now in progress regarding this phenomenon which will, it is hoped, shed new light on the theory of superconducting magnets. There is, needless to say, much work to be done in the field of superconductivity.

It is a formidable problem to design an absolutely "impregnable" magnetic configuration around the basic limitations of superconducting materials. If a suitable design is discovered, the problem of control of the magnet presents itself. It is quite possible that a high-voltage low-current d-c power supply will be available on large space vehicles. (Ion propulsion units require high-voltage supplies.) In order to utilize a magnetic space shield consisting of superconducting windings, the high-voltage low-current d-c supply should be transformed to a high-current low-voltage supply. This could be done by a so-called "d-c pulsed transformer". Such a transformer could regulate the amount of current flowing in the space shield quite easily, and no intermittent mechanical superconducting junctions would have to be made. The proposed operation of the transformer is illustrated in figure 10. The voltage impressed on the secondary would be given by the following relation (ref. 6):

$$e = N \frac{d\Phi_t}{dt} \qquad (2)$$

where Φ_t is the total flux linked by the secondary winding and can be represented by

$$\Phi_t = \Phi_{sec/pri} + \Phi_{sec} \tag{3}$$

where $\Phi_{sec/pri}$ is the flux linked by the secondary due to the primary current, and Φ_{sec} is the flux linked by the secondary due to the secondary current. Equation (2) can also be written as

$$e = M \frac{di_{pri}}{dt} + L_{sec} \frac{di_{sec}}{dt} \tag{4}$$

where $M = N \frac{d\Phi_{sec/pri}}{di_{pri}}$ is the mutual inductance and $L_{sec} = N \frac{d\Phi_{sec}}{di_{sec}}$ is the secondary self inductance.

If the secondary is superconducting, the induced voltage is also given by

$$e = -L_c \frac{di_{sec}}{dt} \tag{5}$$

On integration, equations (4) and (5) yield

$$i_{sec} = \frac{-M}{L_c + L_{sec}} i_{pri} \tag{6}$$

Thus, if the secondary is completely superconducting, any increase in primary current will cause a directly proportional increase in the secondary current if M, L_c, and L_{sec} stay constant. If a resistance is inserted in the secondary, i_{sec} will decay to zero. This can be accomplished by heating a small portion of the superconducting secondary until it exhibits its normal resistance. If the secondary heater is then turned off allowing the secondary to again become superconducting, a reduction of the primary current to zero will induce a current equal to $-i_{sec}$, if all heat losses are neglected. Thus, the space shield would be energized, and no input current would be necessary at the end of the sequence. Further work on this project is being done by the writer with the end result hopefully being an undergraduate thesis for the Electrical Engineering Department here at the University of Cincinnati.

The wide range of subject matter available at NASA lends itself well to the much desired attitude of free constructive research.

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E-2289

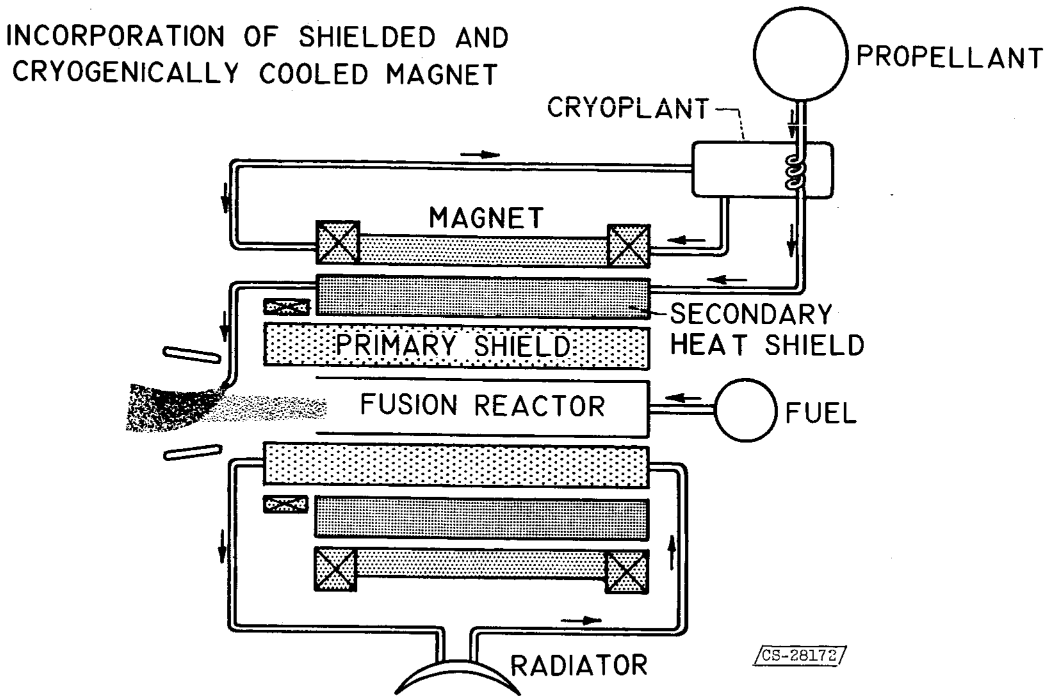

Fig. 1. - Thermonuclear rocket.

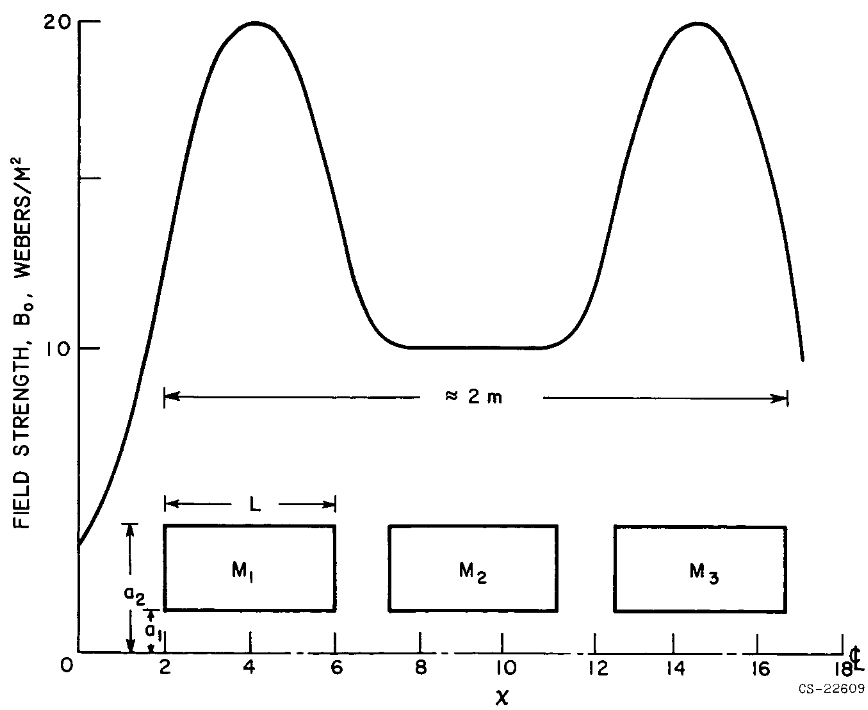

Fig. 2. - Magnetic bottle configuration.

E-2289

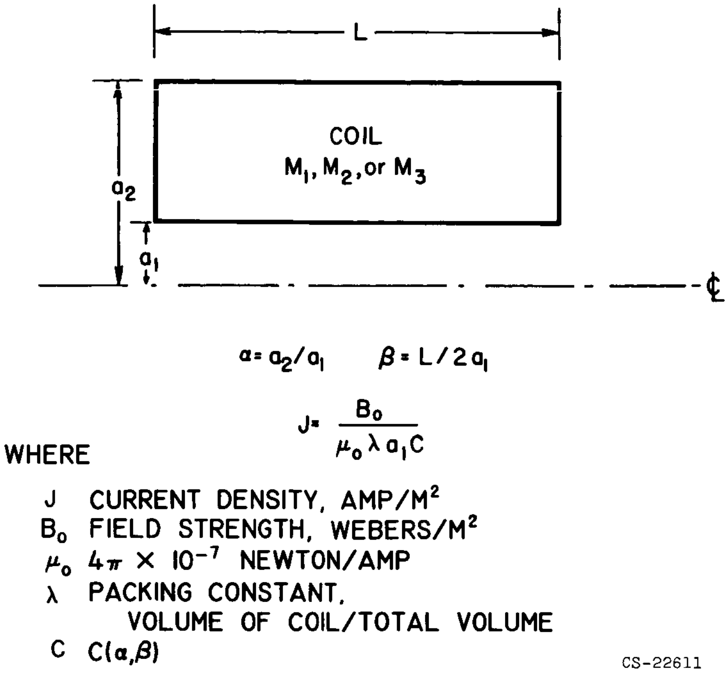

Fig. 3. - Magnet parameters.

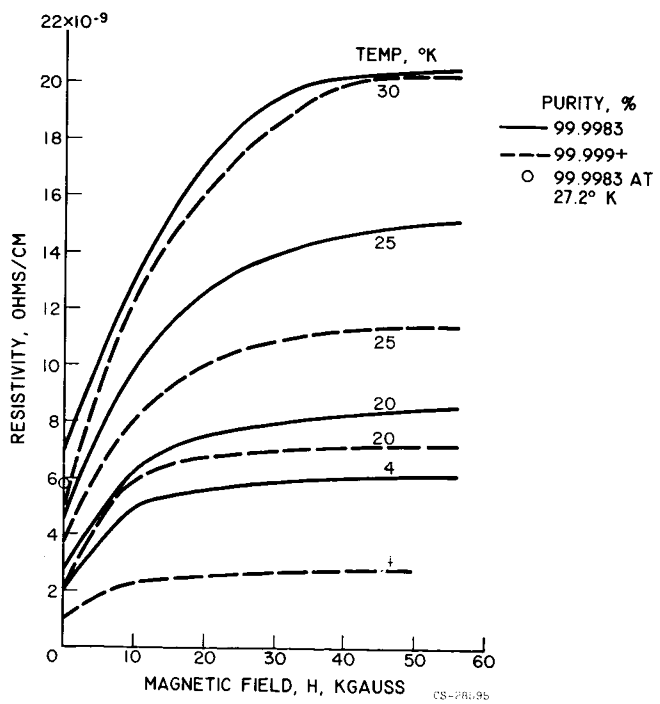

Fig. 4. - Magnetoresistance of aluminum.

E-2289

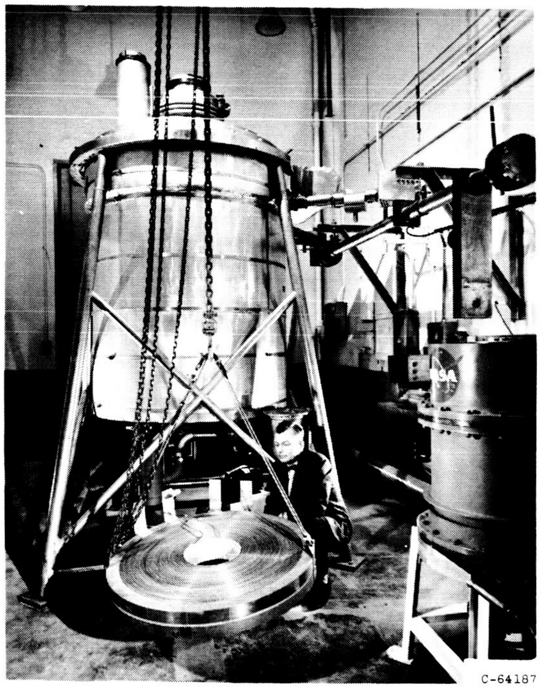

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Fig. 5. - Aluminum coils to be installed in magnet housing.

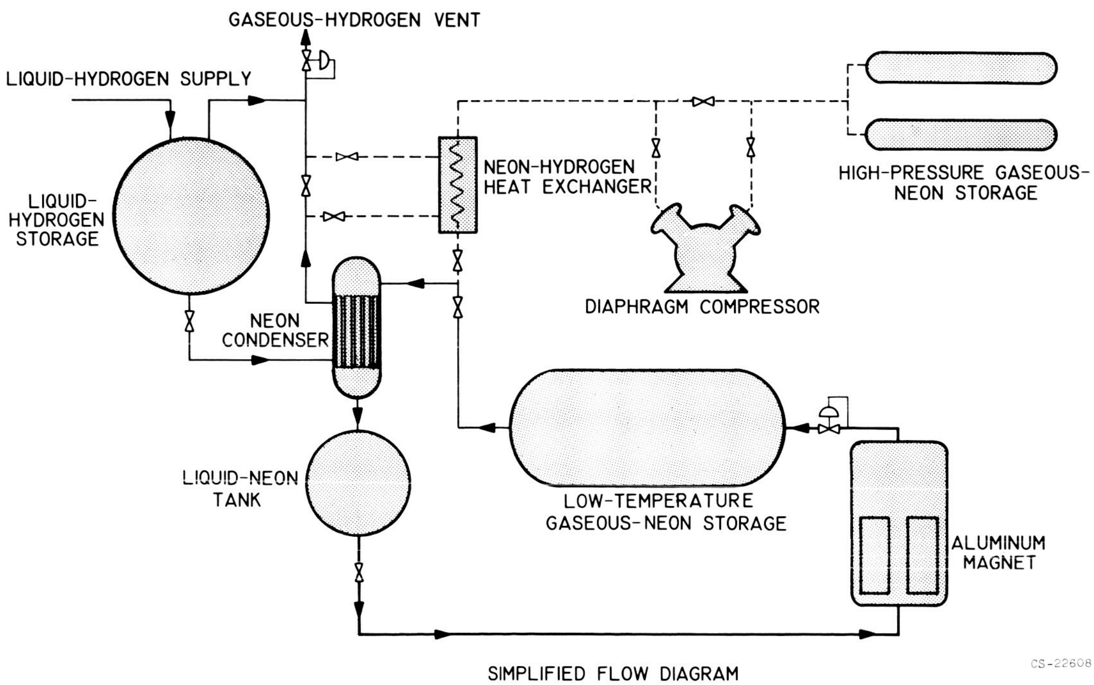


Fig. 6. - Neon refrigeration system for large cryogenically cooled aluminum magnet. All low-temperature vessels and lines are insulated. Nitrogen system is not shown.

E-2289

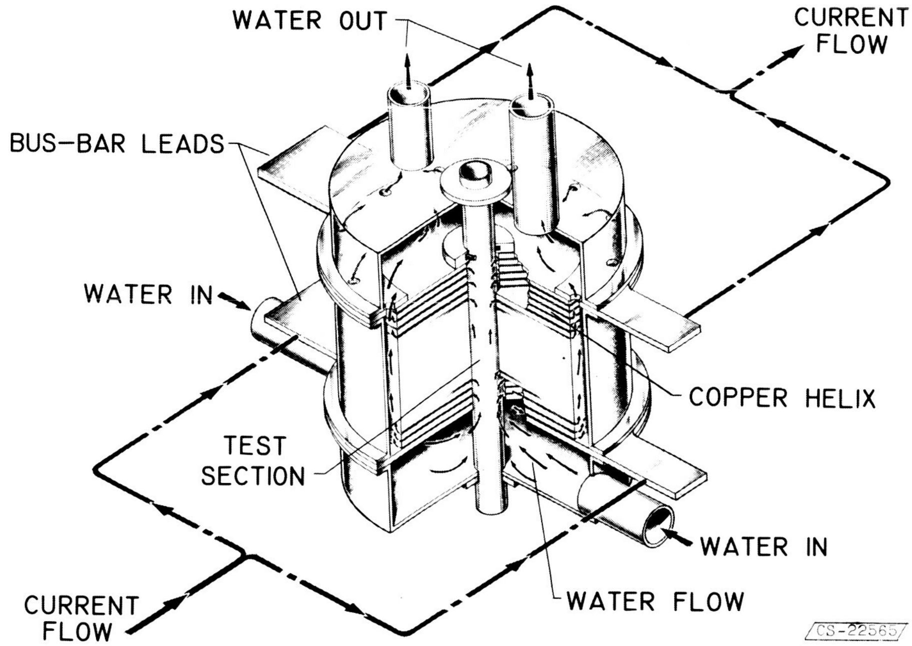
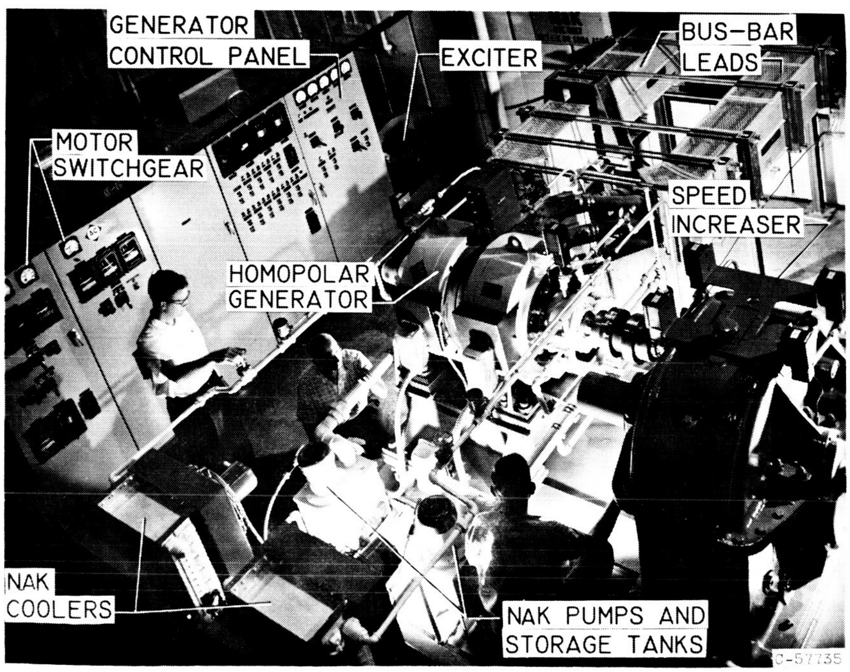
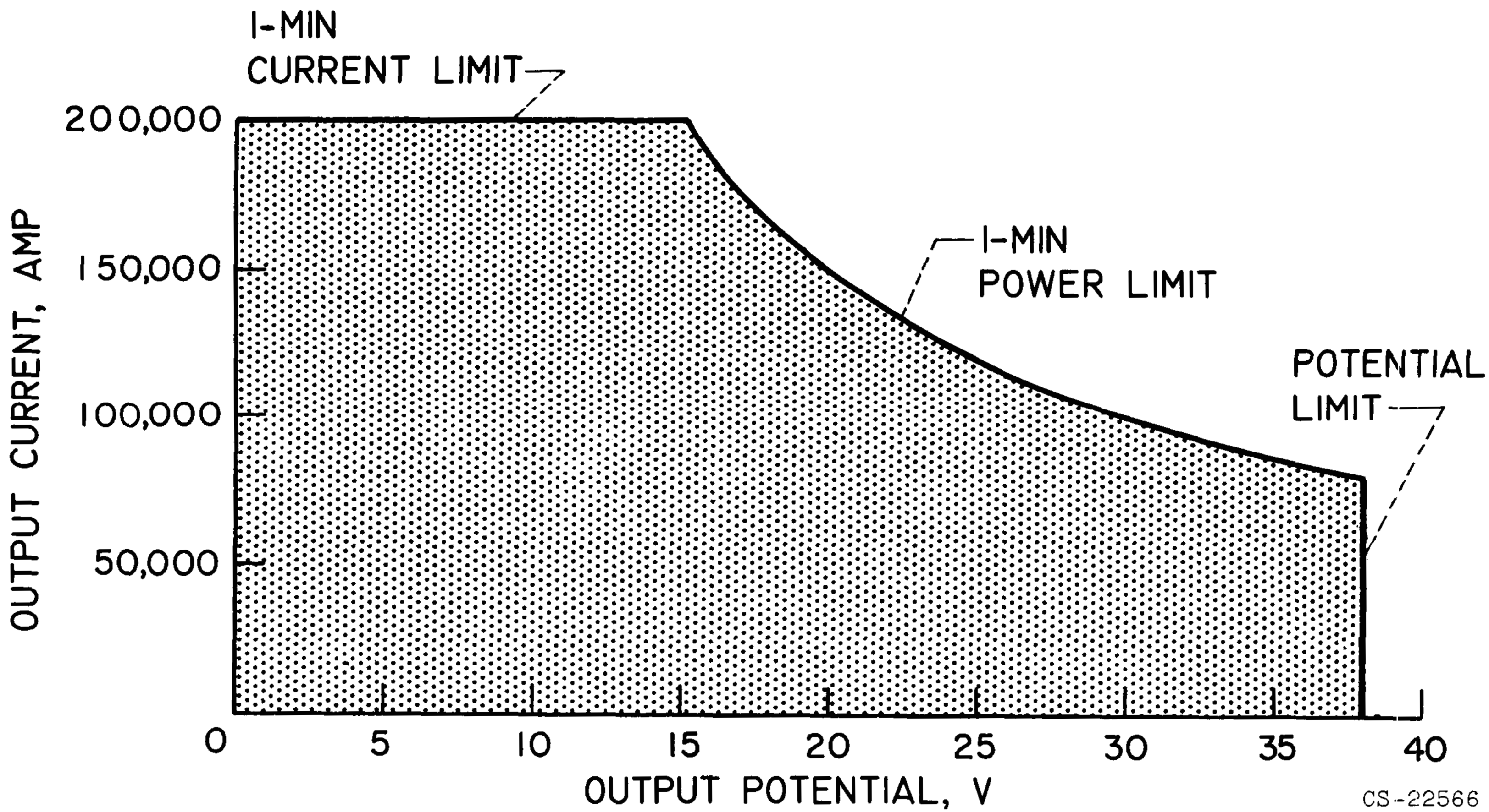


Fig. 7. - 100 Kilogauss water-cooled electromagnet.



(a) Installation. Drive motor is off picture to right.

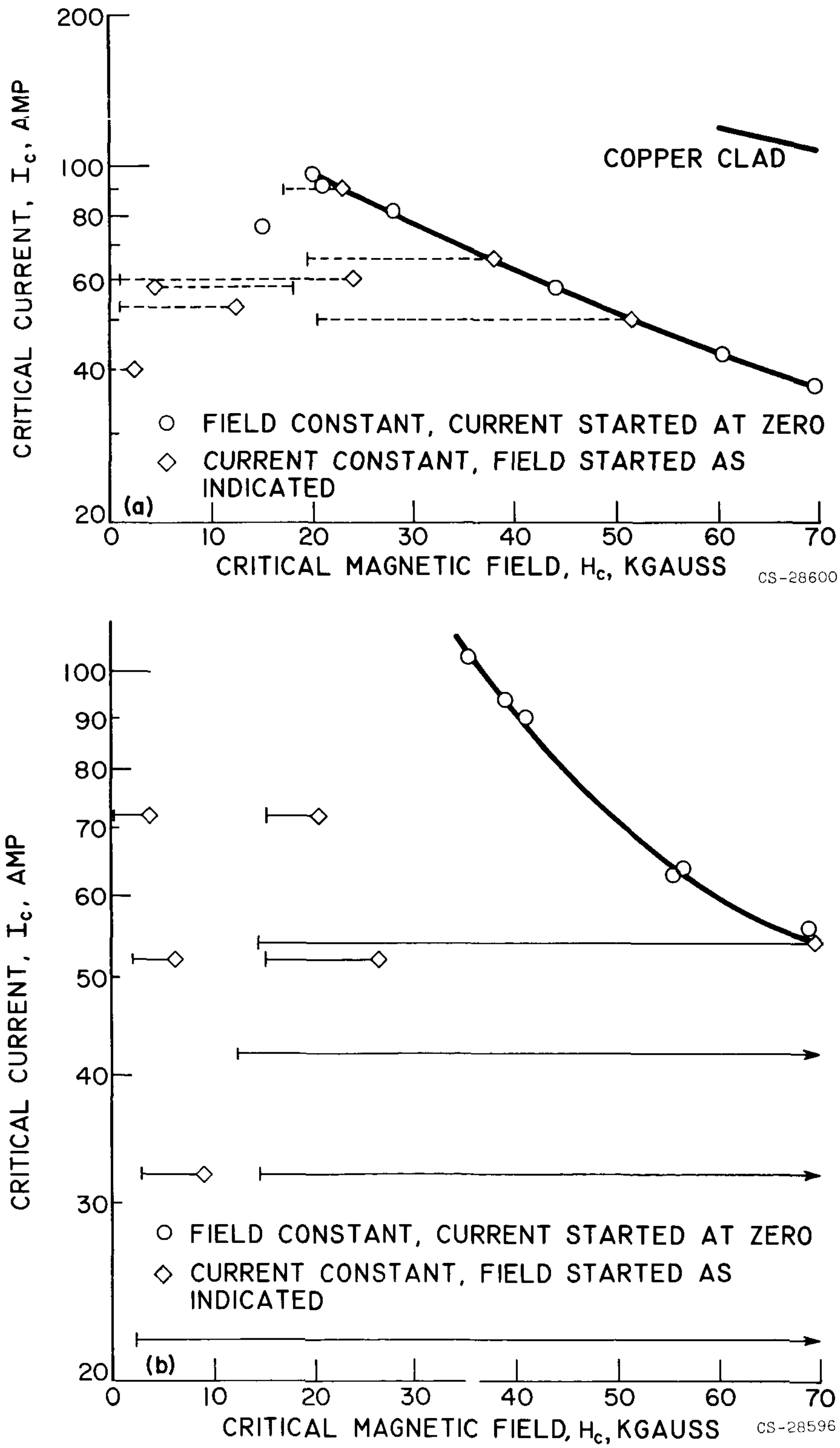
Fig. 8. - Homopolar motor-generator.



(b) Range of operation.

Fig. 8. - Concluded. Homopolar motor-generator.

E-2289

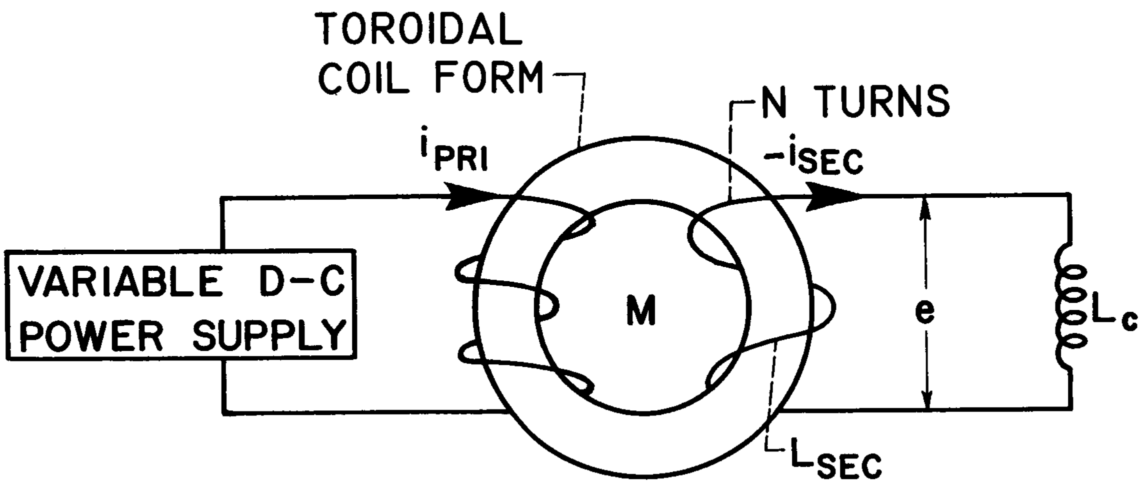


(a) Sample HDC-A.

(b) Sample HDC-B.

Fig. 9. - Critical current as function of critical field for Nb_3Sn ribbon.

E-2289



COIL FORM AND LOAD COIL ARE TO BE IMMERSED IN LIQUID HELIUM

Fig. 10. - Superconducting d-c pulsed transformer.